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A Few Good Rocks:

The Mars Sample Return Mission Architecture

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A Mars sample return is the culmination of many years of exciting missions of the Mars Surveyor Program. Analyzing samples of martian dust and rocks in laboratories on Earth has been a goal of scientists and engineers since the Viking missions in the mid-1970s. Here we describe a snapshot of the current Mars Sample Return (MSR) architecture, which is currently undergoing review and possible change. Launching in August and September 2005, the MSR mission will bring back about 1 kg of martian rocks and soil in April 2008. Like all missions of the Mars Surveyor Program, MSR builds upon previous Mars missions to enable an exciting mission at a fraction of the cost and risk of a stand-alone mission. We describe the MSR science rationale, mission architecture, trajectories, flight systems, and challenges for the current architecture.

A FEW GOOD ROCKS: THE MARS SAMPLE RETURN MISSION ARCHITECTURE

I. Rationale for sample return

Mars is a vast planet. In fact, the surface area is roughly equivalent to Earth's continental land surface areas combined. Exploring and understanding the Red Planet requires observations on a global basis with orbiters. In-situ measurements on the surface are required for ground truth, just as in Earth investigations.

Despite the past, present, and future successes of Viking, Mars Pathfinder, Mars Global Surveyor, Mars 98 Orbiter and Lander, Mars 2001 Orbiter and Lander, and Mars 2003 Orbiter and Lander/Rover, there is a limit to what robotic exploration can observe. Many tests for past or present life require that a sample be brought to Earth laboratories for years of intense study.

Obtaining a good set of samples for return requires that we study Mars with the previously mentioned orbiters, landers, and rovers. These missions allow us to find the most intriguing sites within engineering and budget constraints. This "pathfinding" will allow MSR to return a scientifically exciting set of samples for study.

II. Mars Surveyor Program background

The Mars Surveyor Program has multiple sample returns as a goal (see figure 1). The earliest a sample return is possible, given the current state of knowledge of Mars and the available budget, is 2005. The MSR mission chooses the best site using all orbital and surface data. Then, the mission lands at that site and returns samples of rocks, dust, and soil to Earth. Other sites will be investigated with future MSR missions.

III. Mission Overview

MSR launches on two medium class launch vehicles from Kennedy Space Center in August and September 2005 (see figure 2). The orbiter/Earth Entry Vehicle (EEV) launches on a Delta III or Atlas IIIA first. Then, about a month later, the lander/Mars Ascent Vehicle (MAV) launches on a Delta III or Atlas IIIA class launch vehicle. Other launch vehicles under consideration are:

- Delta IV Medium+ (EELV)
- Atlas IV (EELV)
- Ariane 5 (with and without cryogenic upper stage)

All vehicles will launch from Cape Canaveral Air Force Station, except for the Ariane 5, which launches from Korou, Guyana.

Both the orbiter/EEV and the lander/MAV have cruise stages that provide power and telecommunications capabilities en route to Mars.

After approximately a 1-year cruise to Mars on a type 2 trajectory, the orbiter does an orbit insertion maneuver with its bipropellant system into a large elliptical 12-20 hour period orbit. The orbiter stays in this orbit for a few months until the period of solar conjunction* passes. The current aerobraking scenario then takes 80 days to reach an orbit that is compatible with the MAV.

The lander also uses a type 2 trajectory to Mars. After arriving sufficiently late to avoid the solar conjunction period*, the lander proceeds to enter the martian atmosphere. During the atmosphere entry, guidance and control algorithms guide the vehicle to a precise landing. After sufficient reduction in velocity, the aeroshell and heat shield are jettisoned and a parachute is deployed. At an altitude of a few kilometers above the local surface, the parachute is cut and the lander's rockets begin to fire. The lander then touches down on the surface.

After a checkout period of a few days, the rover deploys and begins to analyze and collect samples of rocks and

* Current navigation studies show that the earliest a lander could arrive is Nov. 29, 2006. This is because the lander must have enough navigation data after the solar conjunction period to be able to execute a trajectory correction maneuver at 10 days before lander arrival at Mars. The date of minimum solar conjunction angle (slightly less than 1°) is Oct. 23, 2006. The orbiter can begin aerobraking around Nov. 15, 2006.

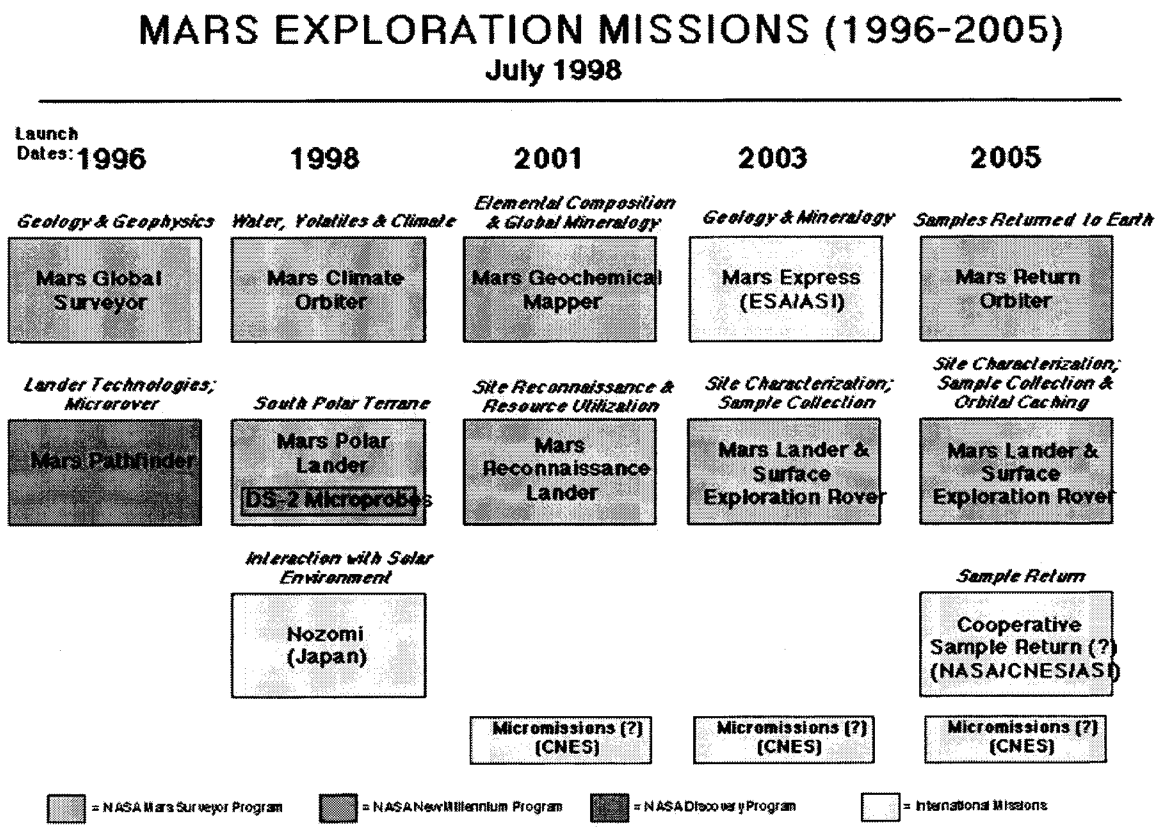

Figure 1. Representative Mars Exploration Program timeline

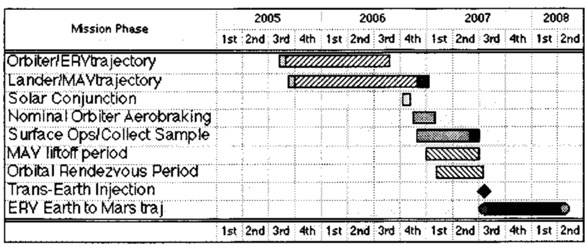

Figure 2. MSR timeline

soil. The rover returns to the MAV to deposit the samples possibly more than once. The MAV then launches from the lander base into a circular orbit of around 300-km altitude (with respect to the martian equatorial radius).

Meanwhile, the orbiter will rendezvous with the MAV after a series of maneuvers taking several weeks. If the orbiter is still aerobraking, the MAV will wait in its orbit until the orbiter finishes aerobraking. Then rendezvous with the MAV by the orbiter will begin. After successful rendezvous, the MAV transfers the samples to the orbiter EEV.

When the geometry is correct for injection to Earth, the orbiter burns once to inject into an elliptical orbit about Mars. Then at apoapsis, any necessary plane change is accomplished, followed by the trans-Earth injection at periapsis.

Close to Earth, the orbiter will do its final targeting maneuvers. After this, it will detach from the EEV, leaving only the EEV to enter the atmosphere ballistically. The EEV is targeted for a touchdown in Australia due to incoming trajectory geometry. We are also looking at the Utah Test and Training Range (UTTR) near Dugway, Utah and the White Sands Missile Range (WSMR) in New Mexico as landing sites.

The sample is returned around May 1, 2008. After initial checks, the sample is transferred to a sample return examination facility and the process of examining the Mars samples can then begin.

A. Launch and Earth-to-Mars trajectory

MSR launches on two small-to-medium launch vehicles. The launch periods for the orbiter and lander are constrained by:

- minimizing the launch energy (C_3)
- minimizing the orbiter arrival V_∞ at Mars (to minimize orbit insertion propellant)

- requiring the declination of the outgoing asymptote of the launch trajectory not to exceed | ~28.5° | (if this constraint is not met, launch injected mass is reduced)
- requiring no critical operations during the solar conjunction period
- leaving at least 10 days between launches to allow sufficient time for final lander launch preparation on the pad
- not allowing the lander arrival V_∞ to exceed 5.5 km/s (the Mars Pathfinder value)
- requiring at least a 21-day launch period for the orbiter and the lander

Satisfying these constraints leads to the orbiter and lander launch periods in August and September 2005, as shown in tables 1 and 2.

Table 1. Orbiter Launch and Arrival Period Characteristics

Launch Date[a]	Arrival Date[b]	C_3[c]	DLA[d]	V_x[e]	DAA[f]
Aug 9	Aug 23	17.83	6.95	3.12	33.55
Aug 10	Aug 23	17.55	6.48	3.11	33.85
Aug 11	Aug 23	17.29	6	3.1	34.15
Aug 12	Aug 23	17.07	5.5	3.1	34.46
Aug 13	Aug 23	16.87	4.99	3.09	34.77
Aug 14	Aug 23	16.7	4.47	3.09	35.1
Aug 15	Aug 23	16.56	3.94	3.09	35.43
Aug 16	Aug 23	16.45	3.39	3.09	35.78
Aug 17	Aug 23	16.36	2.83	3.09	36.13
Aug 18	Aug 23	16.29	2.25	3.09	36.49
Aug 19	Aug 23	16.24	1.65	3.09	36.87
Aug 20	Aug 23	16.22	1.02	3.09	37.26
Aug 21	Aug 23	16.22	0.38	3.1	37.66
Aug 22	Aug 23	16.24	-0.29	3.1	38.08
Aug 23	Aug 23	16.29	-0.99	3.11	38.51
Aug 24	Aug 23	16.37	-1.71	3.12	38.96
Aug 25	Aug 23	16.48	-2.46	3.13	39.42
Aug 26	Aug 23	16.62	-3.24	3.15	39.91
Aug 27	Aug 23	16.81	-4.04	3.16	40.42
Aug 28	Aug 23	17.03	-4.88	3.18	40.94
Aug 29	Aug 23	17.3	-5.74	3.2	41.5

a. in 2005
b. in 2006
c. km^2/s^2
d. Declination of the launch asymptote, in degrees
e. V_∞ at Mars arrival in km/s
f. Declination of the arrival asymptote, in degrees

Table 2. Lander Launch and Arrival Period Characteristics

Launch Date[a]	Arrival Date[b]	C_3[c]	DLA[d]	V_x[e]	DAA[f]
Sep 10	Nov 29	16.21	22.73	4.16	13.72
Sep 11	Nov 29	16.11	22.69	4.16	13.73
Sep 12	Nov 29	16.05	22.65	4.15	13.73
Sep 13	Nov 29	16.01	22.61	4.15	13.74
Sep 14	Nov 29	16	22.57	4.15	13.74
Sep 15	Nov 29	16.01	22.52	4.14	13.74
Sep 16	Nov 29	16.05	22.46	4.14	13.73
Sep 17	Nov 29	16.1	22.4	4.14	13.73
Sep 18	Dec 2	16.17	22.96	4.18	12.99
Sep 19	Dec 5	16.23	23.51	4.23	12.24
Sep 20	Dec 8	16.29	24.05	4.27	11.49
Sep 21	Dec 11	16.34	24.58	4.32	10.74
Sep 22	Dec 15	16.4	25.27	4.38	9.74
Sep 23	Dec 18	16.45	25.78	4.43	8.99
Sep 24	Dec 21	16.5	26.27	4.48	8.23
Sep 25	Dec 25	16.55	26.91	4.54	7.23
Sep 26	Dec 28	16.61	27.37	4.6	6.47
Sep 27	Jan 1	16.66	27.96	4.66	5.48
Sep 28	Jan 4	16.72	28.4	4.72	4.71
Sep 29	Jan 7	16.78	28.82	4.77	3.95
Sep 30	Jan 10	16.84	29.22	4.83	3.19

a. in 2005
b. in 2006/2007
c. km^2/s^2
d. Declination of the launch asymptote, in degrees
e. V_∞ at Mars arrival in km/s
f. Declination of the arrival asymptote, in degrees

The MSR orbiter and lander use a type 2 Earth-to-Mars trajectory (figure 3). Other trajectory types considered were a type 1 (figure 4) and a type 4 (launching in November 2004). The type 4 trajectory has much lower maximum C_3 requirements. But, due to program funding limitations, this trajectory is not feasible. Required MAV propulsion technology development, as well as other technologies to reduce mass and power, need funding early in MSR. This means that the budget to build the flight systems is not ready before a 2005 launch.

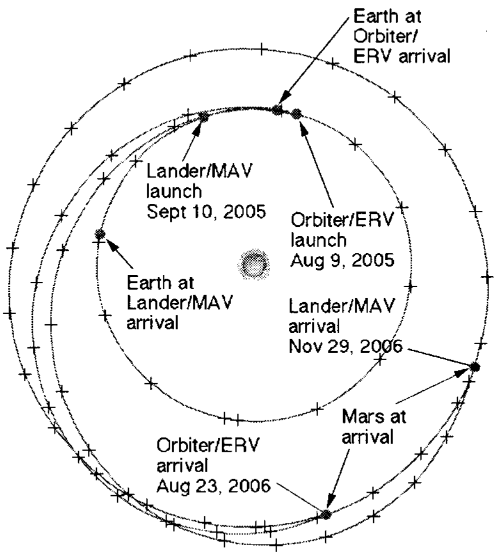

Figure 3. MSR Earth-to-Mars trajectories

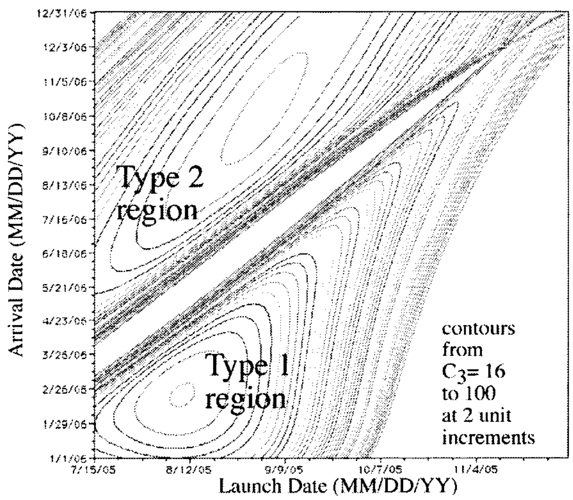

Figure 4. MSR launch period 'porkchops'

The orbiter and lander trajectories utilize maneuver strategies similar to Mars 98 and Mars 2001. There is a post-injection cleanup at about launch +8 days, a mid-course maneuver, a maneuver at about encounter -30 days, a maneuver at about encounter -10 days, and finally a small maneuver at about 10 hours before encounter. After these maneuvers, the orbiter, and later the lander, are targeted to their final Mars aimpoints

B. Operations at Mars

Orbiter. After a Mars orbit insertion (MOI) burn of ~1335 m/s (~145 m/s due to gravity losses), the orbiter is in an 18-23 hour capture orbit, from which aerobraking operations begin (figure 5). Aerobraking proceeds in two phases due to solar conjunction.The first phase lasts from arrival to October 1, 2006. Then, aerobraking operations are suspended due to solar conjunction. The second phase proceeds from November 15, 2006 to completion. The nominal aerobraking period ends when apoapsis decays to ~450 km altitude. We estimate it will take ~80 days of aerobraking passes, which results in finishing aerobraking around January 4, 2007.

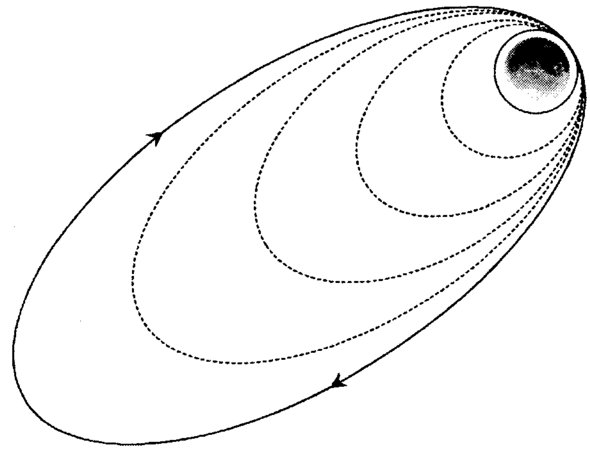

Figure 5. Representative Aerobraking at Mars

After aerobraking, the orbiter will rendezvous with the orbiting MAV. The scenario for this rendezvous is not completely worked out at this time. The current scenario has the orbiter being the active component of the rendezvous. As such, the orbiter communications, navigation, guidance, and propulsion systems, with help from ground operations on Earth, adjust its orbit to match that of the MAV. The MAV has only a beacon to aid the orbiter rendezvous systems.

After rendezvous, the sample is transferred to the Earth Return Capsule on the EEV. Then the orbiter awaits proper alignment of the orbit for the Earth return trajectory.

Lander. The MSR lander jettisons the cruise stage within an hour of Mars atmospheric interface. Then the lander aeroshell orients for the atmosphere passage. As the lander passes through the upper and middle atmosphere, active guidance controls the flight path*. Current studies suggest active guidance achieves a landing on the surface within 5 km (3σ) of a targeted landing site. Precision landing is necessary so that the rover, which

* Precision landing achieves miss distances from a desired surface site of from 10s of kilometers to < 100 meters. This wide range of miss distances depends upon navigation accuracy, atmospheric disturbances, the lander aeroshell and center of gravity, and surface winds. MSR builds upon the knowledge gained from Mars Pathfinder, Mars '98, Mars '01, and Mars '03 to achieve this precise landing.

has a range of a few hundred meters from the lander, can collect the correct samples as determined by the MSR science team.

After the active guidance phase, the lander jettisons the aeroshell and deploys a parachute. Then, within a few kilometers of the surface, the parachute is cut away and retro rockets with active radar bring the lander to rest on the surface.

After checkout of the lander systems and relay of the descent images to Earth, the lander deploys ramps (similar to Mars Pathfinder). The rover drives off and begins to collect samples. The exact procedure for sample collection and transfer to the MAV (sitting atop the lander) is unknown at present and is being investigated.

After sample collection is completed (at 30-180 sols) the flight team on Earth checks the systems and readies the MAV for ascent. The multistage vehicle ascends through the atmosphere and circularizes to a ~300-km-altitude orbit. Then, the MAV awaits the rendezvous of the orbiter. Currently, we are investigating guided and unguided MAV configurations.

C. Mars-to-Earth trajectory

After the orbit lines up correctly for the Mars-Earth trajectory, the EEV does a maneuver to achieve an elliptical orbit. At apogee, any required plane change is accomplished. Then at perigee, a large burn injects the EEV toward Earth. The total ΔV for injecting to Earth is ~2400 m/s.

During the type-2 Earth return (see figure 6), several navigation maneuvers totaling about 40 m/s slowly bias the Earth target aimpoint in toward Earth. For the nominal trajectory, it is not possible to return and land in the continental U.S. due to the incoming asymptote declination of ~-50°. Although at this time we plan a landing in Australia, other options are being investigated. Chief amongst these options is a flyby of Earth followed by Earth return to UTTR 6 months later. The ΔV cost for this option is very small, on the order of 10 m/s or less.

D. Flight systems

Introduction. The flight system described in this paper is based on the reference MSR mission architecture as of July 15, 1998; other concepts are being investigated.

Of the possible launch systems under consideration (see below), the flight system design is constrained by the least common denominator of launch vehicle capability and payload fairing volume. In this case, the mass target for the orbiter is 995 kg and the mass target for the lander is 1800 kg. The maximum allowable diameter is 3.65 m for the lander and the orbiter.

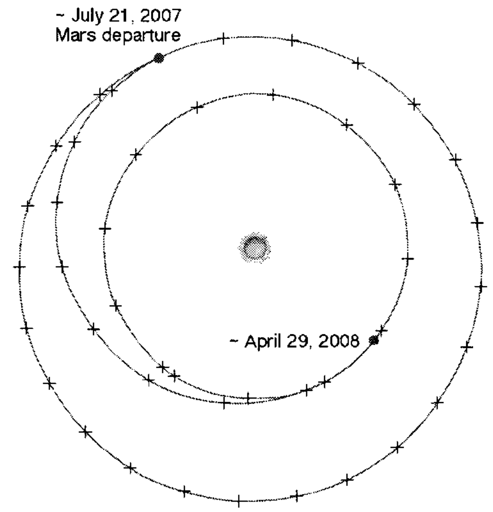

Figure 6. MSR Mars-to-Earth trajectories

In order to reduce launch costs, the architecture baselined for MSR is a Mars orbit rendezvous rather than a direct return to Earth. The flight system is comprised of two main components: the orbiter (cruise) component and the lander (surface) component. The orbiter component includes an orbiter bus and an Earth return capsule. The lander component includes a lander bus, a rover, and a Mars ascent vehicle. The key capabilities of these systems are described below.

Orbiter (*Cruise Component*)

- ORBITER BUS - provides the primary propulsive capability on the way to Mars, at Mars, and on the way to Earth, as well as guidance and communications.
- RETURN CAPSULE - provides a sealed environment that can survive Earth reentry and landing.

Lander (*Surface Component*)

- LANDER BUS - utilizes parachutes and propulsion to soft-land the rover and ascent vehicle near a sample site. Also provides communications to Earth.
- ROVER - deployed after landing to collect samples from the site and return it to the ascent vehicle.
- ASCENT VEHICLE - provides the propulsive capability to launch the sample container into a low Mars orbit to await rendezvous with and transfer of the sample to the orbiter.

Orbiter Bus. The orbiter (figure 7) targets for a propulsive orbit insertion into a 40-hour, roughly 41.5° elliptical orbit at Mars. The mass of the orbiter is driven by the 4-km/s propulsive load it is required to carry to get into Mars orbit and to leave Mars orbit (table 3). The orbiter has two stages in order to reduce mass by jettisoning the first stage before leaving Mars; staging saves roughly 100 kg. Each orbiter stage performs roughly half of the ΔV required by the orbiter.

Some of the orbiter guidelines are:

- Maximum mission lifetime 3.5 years
- Sun range (min/max) .0.987 AU, 1.5 AU
- Earth range (min/max) 1.0 AU, 2.5 AU
- Eclipse duration (max) 3–4 h out of 13 h
- DSN allocation at Mars Continuous 34 m

The propulsion system is dual-mode bipropellant with an Isp = 337 s. The ERC is mounted in the center of the orbiter, which allows the sample container to be inserted on one side without having to dislodge the heat shield on the other side. The orbiter is solar-powered with batteries for eclipses. A combination of solar cells on stage 1 and solar panels mounted to stage 2 provides 8 m^2 of solar area, which generates 210 W of electrical power. When stage 1 is jettisoned, an equivalent area of solar cells to that which was lost due to shadowing on stage 1 is uncovered on stage 2, maintaining a total of 8 m^2. This area is also important to maintain for aerobraking from the high elliptical orbit to a low Mars orbit (250 km circular).

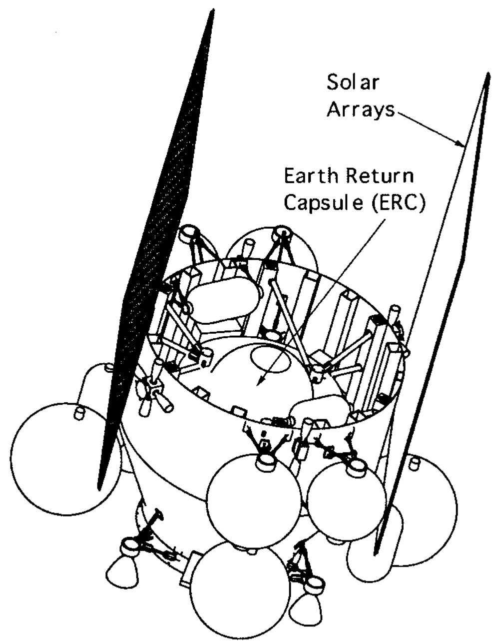

Figure 7. MSR Orbiter

One very important function of the orbiter is to track, rendezvous, and dock with the upper stage of the MAV

Table 3. Orbiter ΔV Budget

Mission Phase	Maneuver	Engine	ΔV	Maneuver Description	Notes
Outbound	MCM1	1B	67.95	Mars Cruise Maneuver #1	correct for launch injec errors (assume STAR-48)
	MCM2	1B	2.59	Mars Cruise Maneuver #2	clean up TCM1
	MCM3	2M	0.11	Mars Cruise Maneuver #3	target to arrival conditions
	MCM4	2M	0.12	Mars Cruise Maneuver #4	target for final MOI aim point
Encounter	MOI	1B	1200.00	Mars Orbit Insetion	Hp = 250 km, T = 40 hrs, 50 m/s for gravity loss
Aerobraking	AB1	1B	8.50	Aerobrake Entry Burn #2, #3, etc...	atmosphere walk-in burn to Hp = 150 km
	AB2+	2M	3.50	Aerobrake Entry Burn #2, #3, etc...	atmosphere walk-in burns to Hp = ~110 km
	Main Phase	2M	30.00	Main Phase Corridor Control	includes corridor control and ACS
	Walk-out	2M	50.00	Walk-out Corridor Control	includes corridor control and ACS
	Conting	1B	25.00	Aerobraking Contingency Burns	one pop-up maneuver to Hp = 165 km
	ABX	1B	38.00	Aerobraking Termination Burn	Ha = 450 km, Hp raise from 140 to 300 km
	NCM	1B	30.00	Nodal Correction Maneuver	up to 0.5 deg. correction for overshoot of MAV node
Rendezvous	ICM	1B	10.00	Inclination Correction Maneuver	3-sigma high of 36 m/s
	ACMs	1B	47.00	Apsidal Correction Maneuvers	3-sigma high of 77 m/s
	ATM	1B	8.00	Apsidal Trim Maneuver	3-sigma high of 28 m/s
	TPI	2M	5.00	Terminal Phase Initiation	two burns 2.5 m/s each, 3-sigma high per burn of 4.5
	RRA	1B	45.00	Redezvous Reserve Allocation	3-sigma RSS of rendezvous manuevers prior to TPI
	TRMs	2M	25.00	Terminal Rendezvous Maneuvers	up to docking, includes fuel for two attempts
Inbound	*Reserve*	1B	50.00	Reserve for Stage 1	anything left over will be applied to DPM
	Staging	1	0.00		
	DPM1	2B	320.00	Departure Phasing Maneuver #1	Hp = 300 km, Ha raise to 1970 km, 20 m/s for grav loss
	DPM2	2B	925.00	Departure Phasing Maneuver #2	Hp = 300 km, Ha raise to 36130, 25 m/s for grav loss
	TEI	2B	1225.00	trans-Earth Injection	B.R=-70000,B.T=50000, 1:10000 bias, 25 m/s grav loss
	ECM1	2B	33.00	Earth Cruise Maneuver #1	B.R=-14000, B.T=30000
	ECM2	2M	6.70	Earth Cruise Maneuver #2	B.R=-600, B.T=26000
	ECM3	2M	1.00	Earth Cruise Maneuver #3	
	LDM	2B	15.00	Landing Site Deflection Maneuver	select either Australia or Kwalajein at E- 60 days
	ECM4	2M	0.30	Earth Cruise Maneuver #4	cleanup and target for final entry conditions
	Staging	ERC	0.00	Return Capsule Release	
	EDM	2B	15.00	Earth Deflection Maneuver	deflect orbiter to Hp = 300 km
	Reserve	2B	30.00		
	TOTAL	**ALL**	**4216.77**		

(described later). The MAV carries the collected sample into orbit, and the orbiter is required to retrieve the sample, install it into the EEV, and bring it back to Earth. The orbiter also provides the telecommunications link from the MAV to Earth. The orbiter transmits at 2 kbps to Earth using X-band to a 34-m DSN antenna. The orbiter tracks the MAV via a GPS-derived system using an L-band link for ranges less than 2000 km and a 100-MHz link for ranges less than 20,000 km; the MAV transmits and the orbiter receives and tracks.

Another important function that the orbiter performs is monitoring sample containment. NASA is required to ensure containment of the Mars samples, not only to keep the samples pure for scientific investigation on Earth, but also to protect our biosphere from any possible contamination. If the orbiter cannot verify that containment is intact or does verify that containment has been breached, the samples must be sterilized or not returned to Earth. The orbiter passively limits sample temperatures to below 0° C for cruise and below 50° C for Earth entry.

Finally, the orbiter must place the EEV on the proper Earth-impact trajectory, release the EEV, and deflect off an Earth-impact course.

Earth Entry Vehicle (EEV). The purpose of the EEV is to transport the Mars samples safely from Mars orbit to the surface of the Earth. The Mars samples are sealed in a sample container on the surface of Mars and taken to Mars orbit by the MAV. When the orbiter docks with the MAV, the sample container is inserted into the EEV (figure 8). The EEV is attached to the orbiter via three hard points aft of the heat shield. The mass of the sample plus the container is less than 2.7 kg. The EEV is spin-stabilized at 2 to 5 rpm for entry.

One unique feature of the MSR EEV is the lack of a parachute. If the EEV had a parachute and the parachute failed, there would be a chance of containment breach if the sample container were not already designed to withstand high G loads. In such a case, the prudent thing to do is to design the capsule and container to survive such a failure mode. However, if the capsule is designed from the beginning to withstand this failure mode, then there is no need for a parachute, which represents a mass impact on the flight system. Thus, the EEV is designed to limit the mechanical loads on the samples to less than 300 G in winds less than or equal to 11 m/s, while the sample container is designed to take 1000 G without breaching. The interior of the EEV is filled with a crushable foam which is designed to take all but 300 G of the impact force. Another advantage of a parachuteless design is that the landing footprint is smaller since the descent is quicker and the dispersions due to winds are

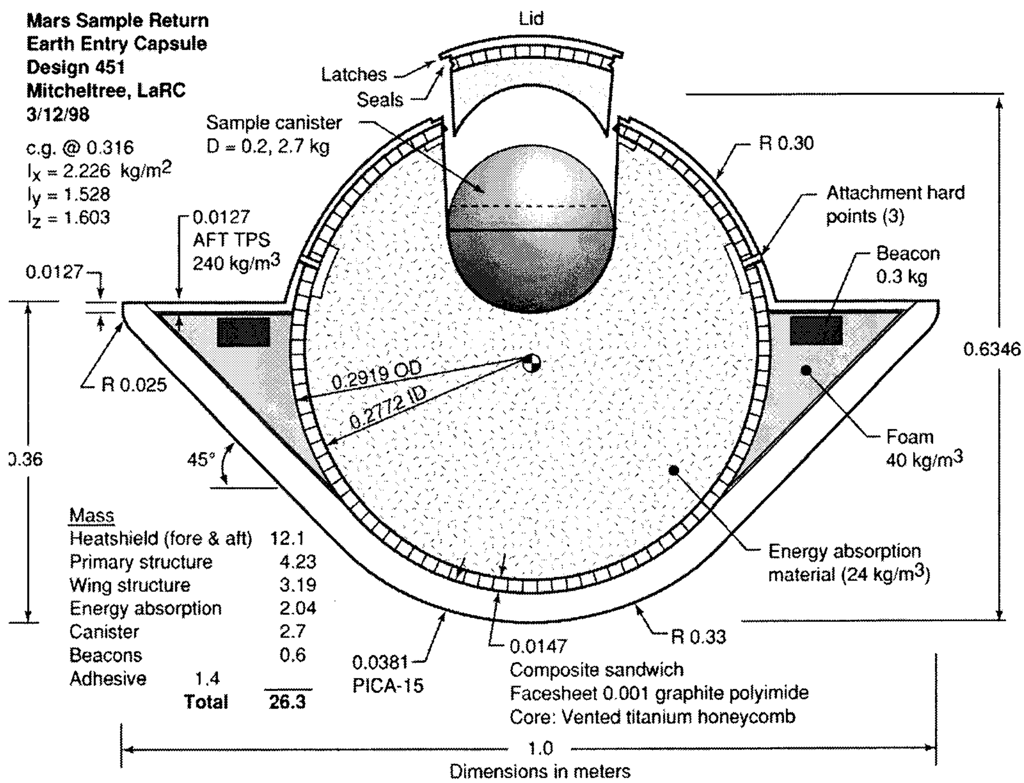

Figure 8. Earth Entry Vehicle

reduced. After landing (velocity = 30 m/s or less), the capsule is located via one of two 242-MHz transmitter beacons in the EEV. The EEV mass, with contingency, is 30 kg.

Lander Bus. The lander (figure 9) is guided by a cruise stage and is mostly dormant during the cruise to Mars (except for occasional checkouts). Before cruise stage separation, the lander systems are brought up and initialized.

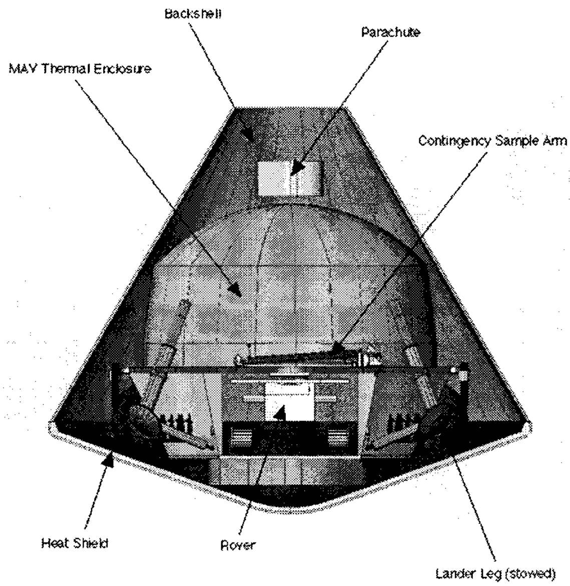

Figure 9. MSR Lander in Aeroshell

The lander uses aeromaneuvering for an inertially guided entry and deceleration in the martian atmosphere*. At the end of the entry phase and after ejection of the heat shield, the lander deploys a parachute to take out some of the downrange error, and the remainder of the distance is covered propulsively by adjusting the time when the excess horizontal and vertical velocity are canceled by the soft lander thrusters. Around 50 m/s ΔV is required for this accurate descent and landing scenario. Four deployable legs on the lander (figure 10) allow for greater than 35 cm of ground clearance in order to avoid large rocks.

Also on the MSR lander is the MAV, the rover, and a contingency sample collection arm. The sample contingency arm is required as a backup in case the rover mission fails. The arm has the capability to grab samples within 2 m of the lander and place the samples inside the sample container.

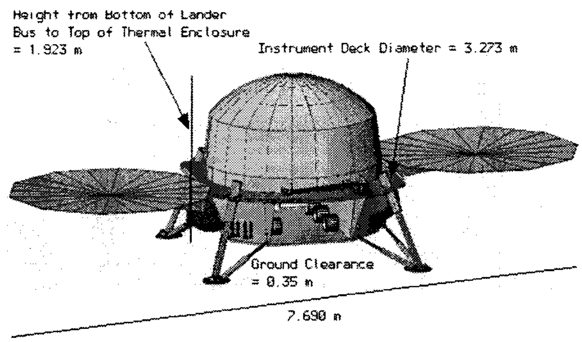

Figure 10. MSR Lander With Legs Deployed

The lander communicates directly to Earth via a high-gain antenna. There is a backup low-gain antenna that can accept commands in case of an anomaly. The MSR telecommunications architecture is shown in figure 11.

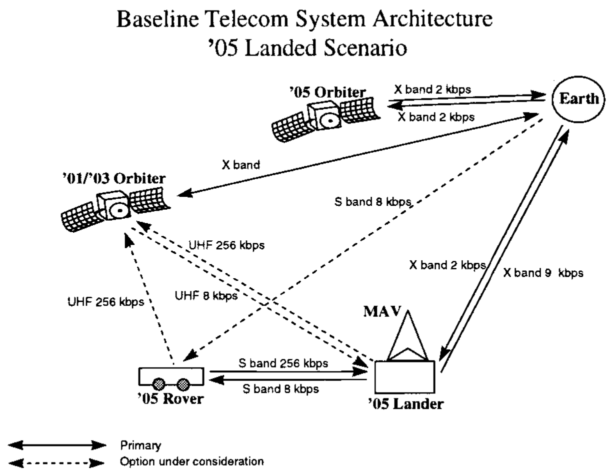

Figure 11. MSR Telecommunications Architecture

Rover and Payload. The rover (figure 12) is equipped with the Athena payload (table 4) which allows it to choose, gather, characterize, and select samples for return to Earth. The maximum number of samples to be collected is still under deliberation and is a function of time required for selection and collection, time required to traverse the surface of Mars, and rover lifetime limitations. One limiting factor on rover lifetime is the amount of solar power able to be collected due to landing season and due to dust accumulation on the solar panel.

To maximize the chances of returning scientifically valuable samples from a variety of sites and rock types, the rover will make three collection loops. The primary

* A center-of-gravity (CG) offset causes an angle of attack during lander hypersonic atmospheric passage. This allows small thrusters, when coupled with precision landing guidance and control, to roll the lift vector of the lander aeroshell as needed. This roll control allows the lander to take out perturbations caused by Mars's atmosphere.

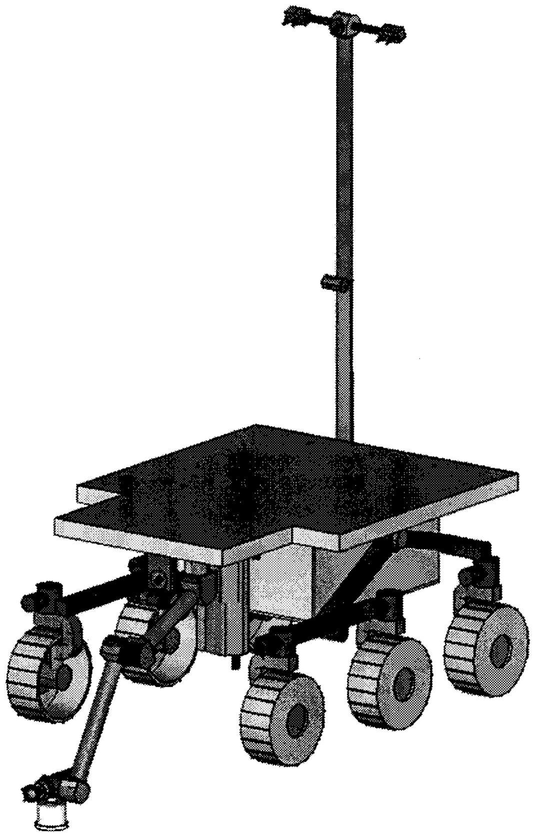

Figure 12. MSR Rover

mission lasts 30 sols*, and the rover will collect up to eight samples in a cache. Once the rover safely returns this cache to the lander, the rover will venture out again, this time for up to 60 sols, and collect up to 12 samples. If the rover returns this cache safely and the MAV can remain on the surface longer, the rover will be deployed again for another sample collection run. For this type of challenging assignment, the rover requires a lot more autonomy than the Sojourner rover had.

The rover is deployed via ramps. The sample cache or the contingency sample will be loaded into a sample container on the lander. That container will then seal shut on the surface of Mars to contain the solid sample and to collect an atmosphere sample. As shown in figure 11, the rover communicates to Earth via a link to the lander or via the Mars '01 or '03 orbiter.

Mars Ascent Vehicle. The MAV itself is a two-stage-to-orbit launch system using storable hypergolic propellants, MMH and MON-25 (NTO with 25% NO). These propellants are being considered for their low boiling point (-40° C) to aid in thermal control on the surface. The vehicle is capable of achieving a low Mars orbit of 300-km altitude.

While surface operations are occurring, the orbiter is aerobraking down to a low circular orbit to facilitate the orbit rendezvous. Once the sample has been retrieved, it is placed by the rover into the lower half of the sample container. That half of the sample container is raised to meet the other half, and the two halves are sealed together and installed onto the end of a long "stinger," which extends through the MAV first stage (figure 13). The MAV would then launch, putting its second stage with the sample container into a similar (but slightly lower) orbit. Launch from Mars requires approximately 4900 m/s of free space equivalent ΔV. The MAV second stage would then simply maintain 3-axis attitude control, pointing to the Sun, and wait for the orbiter. The orbiter would rendezvous with the MAV and transfer the sample.

On the MAV second stage are two navigation aids for the orbit rendezvous: a short-range radio transponder, for direction-finding and accurate ranging from the orbiter; and an active optical target. The radio will be used for long-range tracking, along with orbiter tracking from Earth, to guide the orbiter from a higher, out-of-phase orbit down to the same orbit as the MAV second stage (less than 1 km away) with low relative velocity. The radio will also provide communications between the orbiter and MAV second stage. Those operations are controlled from Earth. The close-proximity phase will be autonomous and will use the optical target, consisting of flashing light sources, synchronized to radio communications from the orbiter for background discrimination, and positioned to enable the determination of the direction, range, and attitude of the MAV second stage. Another option is to use a laser ranging system, which may not require active targets on the MAV.†

At the end of the close-proximity phase when the orbiter and MAV physically dock, the sample container is transferred from the MAV second stage to the return orbiter and placed in the EEC carried by the orbiter. This container transfer will be performed in a way to prevent the transfer of martian material (for example, dust) that might be on the outside of the ascent stage and sample container to the return orbiter and Earth entry vehicle. The current concept is for the sample container to be in a protective sheath that would be deployed upon transfer, with a similar shield on the orbiter that would be

* A sol is a Mars day. A Mars day equals 24 h, 39 min, and 25.245 Earth seconds.
† A laser ranging system reflects laser light generated on the orbiter back from MAV during the terminal rendezvous phase. The time required for the beam to bounce back gives the orbiter an autonomous distance calculation.

Table 4. Athena Payload Description

Athena
Mars Surveyor Rover Payload

Athena Payload Summary

Payload Element	Mass, kg	Peak Power, W	Provider	Heritage	Key Objectives
Remote Sensing Science					
Pancam / Mini-TES	3.41	5.4	JPL / SBRS / ASU	PIDDP, MO, MGS, MSP '01 rover nav cameras	Investigate site geologic setting and processes; determine mineralogy remotely, particularly aqueous materials that may preserve climate and biology evidence; aid in rover navigation
In-Situ Science					
Instrument Arm	1.31	15.9	JPL	Mars Pathfinder, MSP '98	Provide instrument positioning against rocks and soils for Microscopic Imager, APXS, Mössbauer, and Raman Spectrometers
Microscopic Imager	0.075	0.1	JPL	MSP '01 rover nav cameras	Image fine-scale morphology of samples at high resolution; assist in interpreting compositional data
Alpha Proton X-Ray Spectrometer	0.47	1.3	MPI Mainz (Germany) / U. Chicago	Mars Pathfinder, Mars '96	Determine abundances of rock-forming elements; provide fundamental knowledge about crust formation, weathering processes, and water activity
Mössbauer Spectrometer	0.47	1.6	TU Darmstadt (Germany)	Lab instruments, Mars '96/'98	Determine iron oxidation state; detect and identify Fe-carbonates, sulfates, nitrates, and minerals that could preserve early environmental and biological evidence
Raman Spectrometer	1.75	2.5	JPL	Lab instruments, PIDDP	Precisely identify major and minor rock-forming minerals; identify aqueous minerals and organic compounds
Sample Collection and Storage					
Mini-Corer	3.97	17.0	Honeybee Robotics/ JPL	NASA Technology Program, Honeybee Internal R&D	Drill and collect 1.7-cm long rock cores from up to 5 cm within boulders and bedrock; collect soil samples
Sample Container	0.5	5.0	JPL		Retain 91 rock cores (with option to replace 39 cores) and 13 soil samples in sample container to be returned by '05 mission

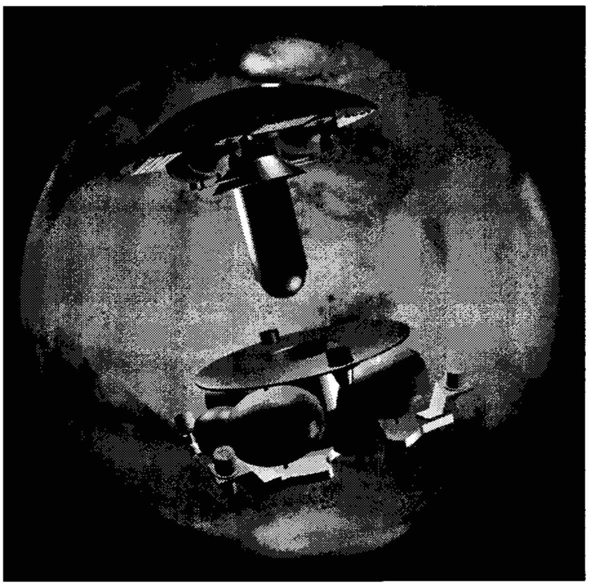

Figure 13. MAV with "Stinger" Holds Onto ERC

ejected after transfer. The ascent stage of the MAV is discarded with the shields after the sample container is successfully transferred. The mass of the MAV is ~520 kg.

IV. Conclusions

As of this writing, the Mars program architecture is undergoing reevaluation by expert scientists, engineers, and astrobiologists from around the world. While the outcome of this evaluation for the Mars program after the 2001 mission is unclear, one thing is certain: NASA and JPL are planning a series of Mars sample returns. Another certainty is that the first of these sample return missions will launch in August/September of 2005.

In about 10 years, we will have our first sample from one of our neighboring planets. The MSR mission is very challenging in many ways. Performance, new technologies, cost, schedule, and risk management all require new techniques and thinking from the engineers and scientists tasked with developing this mission. The payoff is a set of Mars samples that will shed new light on the martian environment and our place in the cosmos after the world's laboratories begin analyses in 2008.

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Acronyms

AU	astronomical unit
CG	center of gravity
DSN	Deep Space Network
ΔV	delta-V (change in velocity)
EELV	Evolved Expendable Launch Vehicle
EEV	Earth Entry Vehicle
ERC	Earth Return Capsule
GPS	Global Positioning System (at Earth)
JPL	Jet Propulsion Laboratory
LeRC	Lewis Research Center
MAV	Mars Ascent Vehicle
MMH	monomethyl hydrazine
MOI	Mars orbit insertion
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
NO	nitrous oxide
NTO	nitrogen tetraoxide
UHF	ultrahigh frequency
UTTR	Utah Test and Training Range (near Dugway, Utah, U.S.A.)
WSMR	White Sands Missile Range (New Mexico, U.S.A.)